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A Method for Detecting Very Small Changes in Capacity and its Application to Changes in Capacity of an Air Condenser Due to Pressure and Humidity Variations

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A DISSERTATION

SUBMITTED TO THE FACULTY OF SCIENCES OF
THE CATHOLIC UNIVERSITY OF AMERICA
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE
DEGREE OF DOCTOR
OF PHILOSOPHY

BY
GEORGE DANIEL ROCK

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THE CATHOLIC UNIVERSITY OF AMERICA, WASHINGTON, D. C.
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CONTENTS

CHAPTER		PAGE
I.	The Purpose of the Investigation	5
II.	The Method of Investigation	5
III.	The Apparatus and its Manipulation	6
IV.	The Experiment	10
V.	The Results	12
VI.	The Discussion of Results	18
VII.	Vita	19

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I. THE PURPOSE OF THE INVESTIGATION

The changes in the capacity of an air condenser, as ordinarily used, are due chiefly to variations in pressure, humidity, and temperature.

The effect of pressure change from atmospheric conditions to that of a vacuum on the capacity of an air condenser has been determined indirectly by several investigators. This has come about in the attempts to measure the dielectric constant of air. Fritts, Zahn, and others in the determination of the dielectric constant of gases used systems which required a change in pressure in order to detect changes in the dielectric constant. But the effect of humidity changes has not been determined over any considerable range. Most observers waited until dry days to make their readings or else made some special arrangements for the maintenance of the humidity at some constant value. The temperature is so easily kept constant that effects due to its variation do not need any particular consideration.

There is need of knowing not only capacity variation through a considerable range of pressure but also through a like range of humidity, and particularly to find out the effect of these changes on the natural frequency of an oscillating circuit containing the air condenser because such condensers are extensively used in radio. When this condenser is used in a tuned radio circuit it is desired to know the detuning effect of a pressure or humidity change.

Through knowledge derived from the experiments of others, it was clear that the change in capacity due to a pressure variation was of a very small order. Using the value 1.00057 as the dielectric constant of air under normal conditions and 0.00000 as the dielectric constant of a vacuum it can easily be shown that the effect of a pressure change is negligible. However, there remains the question of both pressure and humidity changes in the same condenser under the same conditions.

II. METHOD OF INVESTIGATION

Several methods were available for detecting and measuring changes in capacity in an oscillating circuit. The first and the

one most often used is the well-known resonance method. This method requires the use of a high frequency generator of constant frequency and some device for detecting the resonance point. This device usually takes the form of a sensitive thermo-galvanometer in which resonance is indicated by the maximum deflection of the needle. For radio purposes this is sufficiently sensitive but in this investigation the sensitivity was not sufficiently great and the data obtained not self-consistent.

As a modification of the above method, a thermionic voltmeter was then tried in place of the thermo-galvanometer, and this again proved to be too insensitive. A still further modification, consisting in detuning a certain equal amount from resonance on either side, was attempted. While the latter modification gave results considerably better than those obtained by the use of the resonance point, a great lack of agreement was noticed in the results actually observed. This method of resonance, tried in three different ways, therefore proved too insensitive.

Another method, a bridge method, using a high frequency generator and a quadrant electrometer as the detecting unit, was planned. This method was originally outlined by Cagniard.[1] He claims to have obtained by it very self-consistent results. The underlying principle is that the variation in the position of the needle of the electrometer results in a variation in the capacity of the system, and this is compensated for by varying the standard condenser in the bridge system. However, this method was abandoned due to the inability to secure early enough the proper suspensions for the quadrant electrometer. It is hoped, however, to develop this method. It gives promise of improvement over some of the existing methods, since the circuit contains few variables which might lead to complications and to errors.

There remained but one method of sufficient sensitivity, namely, the heterodyne system for detection of small changes in capacity. In this method a very small change in the capacity of an oscillating circuit, which is coupled to a like circuit of unvarying frequency, produces a rather large change in the difference frequency. This method was finally decided upon.

III. THE APPARATUS AND ITS MANIPULATION

Two vacuum tube oscillators were constructed especially for the experimental study and were of the familiar Hartley type.

[1] M. L. Cagniard, Comptes Rendus, 25, 1528 (1926).

The inductances used were wound with thirty turns on a six-inch form of No. 20 d.c.c. copper wire. The condensers were of the low loss type variable in capacity from 0 to 2000 m.m.f. The filament tap was brought to the middle point of the coil in each case. High capacity lead storage cells were used as the source of filament current. For the plate current supply standard "B" batteries of 90 volts were used for each oscillator.

The oscillating circuit "A" was one of practically constant frequency. The condenser under test formed a part of the capacity of the second circuit "B." In parallel with this condenser was a precision condenser K which had been previously standardized. The usual lever of this condenser was removed and a 24-inch insulated arm inserted, and by means of an arrangement of pulleys and string this arm could be raised or lowered from a distance sufficiently great so that the body capacity of the operator would not effect the operation of the circuits. In order to read this condenser, a mirror and telescope were arranged so that the operator having set the condenser from his chair could also determine the reading of the condenser.

The two generators were coupled very loosely by means of inductive coupling, the difference frequency brought to the detector and then to a three-stage vacuum tube amplifier which contained a pair of telephones in the plate circuit of the output tube of amplifying circuit. Varying the capacity in either circuit would, of course, alter the difference frequency, and if this frequency was below 10,000 cycles per second it could be heard in the telephones.

Oscillator "B" was then adjusted to zero beat by means of the precision condenser and the setting of the condenser recorded. The pressure on the air condenser was changed, and the precision condenser K was again adjusted until no beats were present. Two very great difficulties immediately presented themselves. The first difficulty was due to the fact that the two oscillators would drop into synchronism. This period of zero beat would continue over quite a range of the precision condenser. Working then towards a zero beat from each side of the zero point helped considerably and gave far better results. But these were still far from satisfactory, as their deviation from the mean value was too great. The second difficulty was due to the fact that the change in capacity caused by the pressure change was not suffi-

ciently great to make any appreciable change in the setting of the precision condenser.

The first of these two difficulties was overcome through the use of a system of tuning to a definite audio frequency instead of to zero beat. The idea of tuning to some predetermined frequency is not new, as it has been used by many investigators. Fritts[2] used a motion picture film in conjunction with a tuning fork and a special shutter arrangement. This resulted in a print of the tuning fork frequency and a superimposed beat frequency. While this very ingenious arrangement gave good results, it was necessary to develop and print the film before the beat frequency could be determined.

Zahn[3] used a telephone and near it placed an electron-driven tuning fork and relied on tuning by means of the beats as heard by the operator.

Eccles used this device in a slightly different form. Whiddington[4] used another valve oscillator as his standard tone. Mott-Smith and Daily,[5] in the Norman Bridge Laboratory of Physics of the California Institute of Technology, used a mirror attached to an oscillograph and another mirror connected to a tuning fork. The mirror of the oscillograph reflected light from a pinhole into a telescope and oscillated the beam up and down. The same beam of light was reflected from the mirror onto the tuning fork which caused the spot to oscillate horizontally. This resulted in the production of Lissajous' figures and gave a good means of detecting a frequency change.

The apparatus and method finally adopted was considerably different from any of those mentioned above. A 1,000-cycle generator, controlled by a tuning fork, was connected to the output of the last tube of the amplifying system and a sensitive thermo-galvanometer electrically connected to both. In parallel with the galvanometer was a high impedance head-set. This connection is shown in the circuit diagram. The telephones were used to get a rough balance, and the needle of the galvanometer indicated then the exact balance. If the output frequency of the two generators was 1,001 cycles, the needle of the galvanometer would travel slowly from zero to a maximum value and

[2] E. C. Fritts, Phys. Rev., 23, 345 (1924).
[3] C. T. Zahn, Phys. Rev., 23, 781 (1924); 24, 401 (1924).
[4] R. Whiddington, Phil. Mag., 40, 634 (Nov. 1920).
[5] Mott-Smith and Daily, Phys. Rev., 24, 400 (1924).

then return to zero. Exact balance could be detected by the absence of motion of the needle of the meter. It is my belief that this system is superior to the ones previously mentioned, inasmuch as it has all the advantages of the others and in addition has a more accurate method of detecting absolute balance. With this device a person can detect and maintain a difference frequency of less than one part in a million.

As far as I have been able to ascertain, this method of investigation is entirely new and was developed here in our laboratory.

The second difficulty, already referred to on page 6, was overcome by the use of a condenser of rather large capacity placed in parallel with the precision condenser K and then connecting the combination in series with the condenser under test. This method gave a good readable change in the setting of the condenser K as caused by the change in pressure. The system is very similar to that used by Zahn in his determination of the dielectric constant of various gases.

A still further difficulty arose when it was found that the "drift" of oscillator "A" was of a sufficient magnitude to disturb the constancy of the readings. This "drift" was compensated for by the use of a condenser which could be placed in the circuit so as to substitute for the condenser under test. In this way the difference frequency could be adjusted to 1,000 cycles before the taking of the observations, and then, by means of a special double throw switch, the test condenser could be reinserted in the circuit and a reading obtained. The switch could be thrown again and a check reading obtained, thus insuring an accurate reading of the test condenser.

This "drift" was brought under control by means of a very small variable condenser placed in parallel with the condenser of oscillating circuit "A." This small condenser could be manipulated from the operator's position.

The frequency of oscillation used in the experiment was determined in the ordinary way by the use of a calibrated wave meter using a sensitive thermo-galvanometer as the indicating device.

The mechanical features of the apparatus consisted essentially of a device for holding the condenser under test, an air pump to control the pressure, a pressure gauge, thermometers, and hygrometer; and for the humidity tests, a drying system, a reservoir for the air, and a method for saturating the air.

A bell jar with one lead for the condenser connected through

the top and with the second lead connected to the plate at the bottom served as the mounting of the condenser. The bell jar was sealed by means of a special wax compound which provided a satisfactory joint. The pressure gauge was of the ordinary manometer type ranging from barometric pressure to zero. The pump was of the Hyvac type manufactured by Central Scientific Co. and was capable of a vacuum of .001 mm.

The humidity was recorded by means of a hygrometer of the hair type. This was adopted because it is extremely sensitive to changes in humidity and records this change quite rapidly. The drying system consisted of a bubbling tube containing concentrated sulphuric acid connected to a drying tower which contained calcium chloride in the lower compartment and phosphorus pentoxide in the upper compartment. The air which passed through this system was stored in a reservoir containing more phosphorus pentoxide. The reservoir was so arranged that it could be connected to the bell jar directly. The saturating apparatus was made of two bubbling tubes arranged in cascade through which the air was forced to pass. This apparatus could also be directly connected to the bell jar. By properly choosing the proportions of dry and wet air, any desired humidity could be secured.

The hygrometer was calibrated by means of sulphuric acid solutions in conjunction with an Alluard dew point apparatus, thus giving a double check on the accuracy of the hygrometer.

IV. THE EXPERIMENT

The procedure as finally adopted was essentially as follows:

Oscillator "B" containing the precision condenser K and the condenser under test was adjusted so that in conjunction with oscillator "A" a resulting difference frequency of 1,000 cycles was obtained. The setting of the condensers was noted. Air was withdrawn from the bell jar until the pressure was less than one millimeter of mercury. Dry air was allowed to enter and then pumped out. This procedure was repeated twice, in order to insure a dry chamber and to have the bell jar in an evacuated condition. The switch controlling the standard and test condensers was so placed that the test condenser was in the circuit, the oscillator again adjusted to give a difference frequency of 1,000 cycles. This final setting of the precision condenser was

noted. The standard condenser was then connected so as to replace the test condenser, and the standard adjusted until the same frequency was obtained. Then the standard was left unchanged for the remainder of the run.

Air was allowed to enter the bell jar until a pressure of two cm. was noted. The test condenser was again placed in the circuit and the precision condenser varied until a difference frequency of 1,000 cycles was again obtained. This procedure was followed until atmospheric pressure was reached.

The method used in obtaining the capacity changes due to humidity variations was the same essentially. The air in the bell jar was removed, fresh dry air admitted and then withdrawn. This process was repeated twice, then dry air at atmospheric pressure was placed in the bell jar. Readings of the condensers were taken as before. Part of the dry air was then withdrawn and air which had been previously saturated allowed to enter to replace the dry air. After equilibrium had been reached readings were made as before. This was repeated until saturation was reached within the bell jar. This system resulted necessarily in fewer readings than the corresponding pressure run, as about two hours were allowed between each observation, so that the humidity would be the same throughout the bell jar.

The calibration of the condenser system was performed in the following manner: The condensers within the range of the precision condenser were inserted one at a time in the oscillating system "B" and oscillator "A" adjusted so that 1,000 cycles were detected by the usual means. This was done at a frequency higher than the resonance frequency and again at a correspondingly lower frequency. The mean of the values thus obtained when the precision condenser was substituted and adjusted for the same capacity gave the capacity of the unknown condensers in terms of the standardized precision condenser.

For capacities larger than that of the precision condenser, a known calibrated condenser was placed in parallel with the precision condenser. In this way the resultant capacity could be made great enough to allow the use of the same procedure as outlined above. The capacity of the leads to the test condenser was determined by noting the capacity with the condenser in place and then with the condenser removed.

The calibration of the hygrometer was obtained by placing under the same bell jar, the hygrometer, the Alluard dew-point

apparatus, and the previously prepared sulphuric acid solutions. The dew-point apparatus was operated by means of rubber tubing connected to the pressure bulb which was controlled from the operator's position. In this way a double check on the hair hygrometer was secured.

V. THE RESULTS

Using the substitution method of determining the capacities employed in the experiment, it was found that they were as follows:

Capacity of the test condenser plus leads was 2047.65 m.m.f.
Capacity of the test condenser without leads was 2032.50 m.m.f.
Capacity of the condenser in parallel with the precision condenser was 9,750.0 m.m.f.

The following formula gives the relations existing in the circuit used:

$$\frac{1}{K+K'}+\frac{1}{C}=\frac{1}{K+K'+\Delta K}+\frac{1}{C+\Delta C}$$

This held true as the total capacity of the oscillating circuit remained unchanged throughout the runs of pressure and humidity changes. Therefore the expression for the increment in capacity of the test condenser is as follows:

$$\Delta C=-\left[\frac{C^2}{(K+K'+C)\,\Delta K+(K+K')^2}\right]\Delta K$$

where C is the capacity of the test condenser expressed in micro-micro-farads, K is the capacity of the precision condenser, K′ the capacity of the condenser placed in parallel with the precision condenser, ΔC the increment in capacity of the test condenser.

Using the method as adopted by C. T. Zahn[6] so that calculation may be simplified, the approximation that the differential coefficient dK/dC is a linear function of K was used. In this way an average value of dK/dC was obtained, resulting in the equation:

$$\Delta C=-\left[\frac{C}{K+\frac{1}{2}\Delta K+K'}\right]^2\Delta K$$

[6] C. T. Zahn, Phys. Rev., 24, 401 (1924).

For the purpose of this investigation the coefficient of ΔK was found to be practically a constant and has been treated as such in the following computations.

The calculation of ΔC resulted as follows:

$$\Delta C = -\frac{(2047.65)^2}{[876.5 + 9750 + \frac{1}{2}(34.5)]^2}\Delta K$$

$$\Delta C = -.03723\,\Delta K$$

Using this value, $\Delta C = -.03723\,\Delta K$, the respective increments in the capacity of the test condenser were computed for the pressure and humidity series of observations. These computed increments are collected into Tables I and II.

It was found that the change in capacity of the condenser corresponding to a change in pressure from one millimeter to that of atmospheric pressure was only 1.272 m.m.f., while the capacity of the condenser at atmospheric pressure was 2032.50 m.m.f. This gave a change of only 0.06261 of one per cent. Table I shows the results obtained for a typical run under the usual conditions of operation.

The value 1.000572 has been used freely as the dielectric constant of air at O°C and at 760 mm. pressure. Taking this value and assuming that the entire capacity of the condenser was formed through the use of air as the dielectric, the change in capacity in going from atmospheric conditions to zero pressure was computed and found to be in excellent agreement with the experimental values obtained in this experiment. Thus:

$$\frac{760}{754 \times 300} \times 273\,X = .000572$$

$$X = .000624$$

$$\Delta C = .000624 \times 2032.5$$

$$= 1.269 \text{ m.m.f.}$$

In the reverse sense it was calculated that the dielectric constant as determined in this experiment was equal to 1.000578, which value is very close to that usually accepted and falls between the results obtained by Zahn[7] or Fritts[8] and those

[7] C. T. Zahn, Phys. Rev., 24, 401 (1924).
[8] E. C. Fritts, Phys. Rev., 23, 345 (1924).

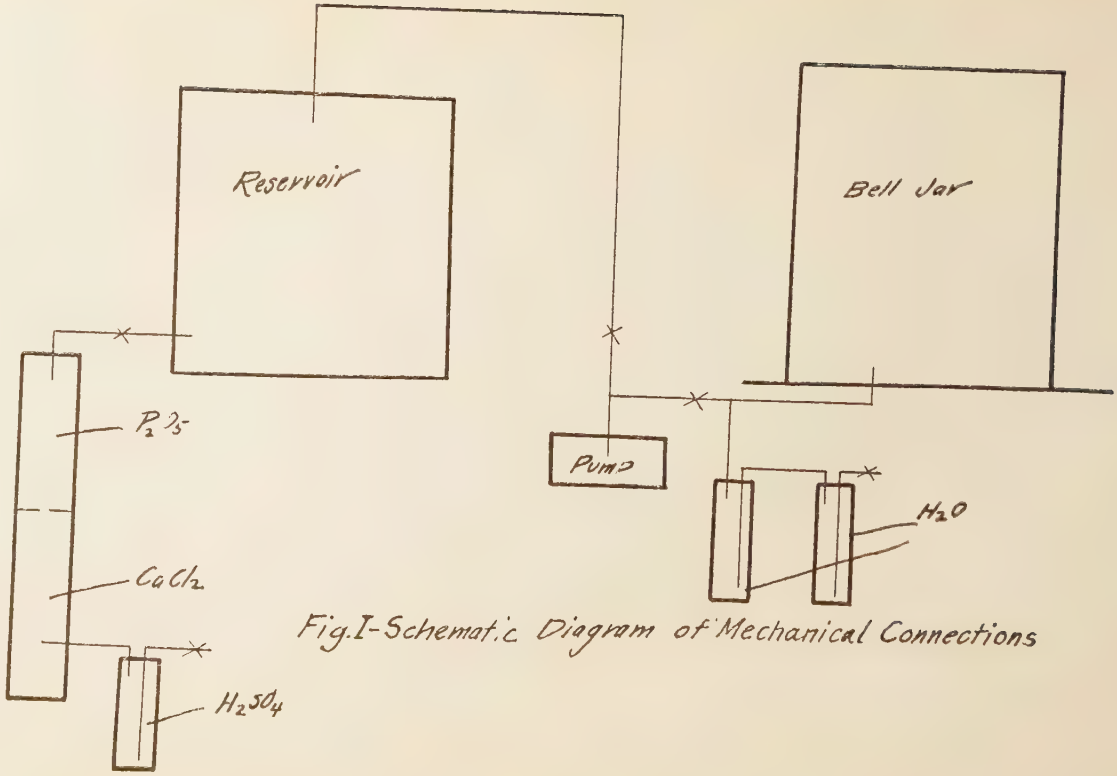

Fig. I - Schematic Diagram of Mechanical Connections

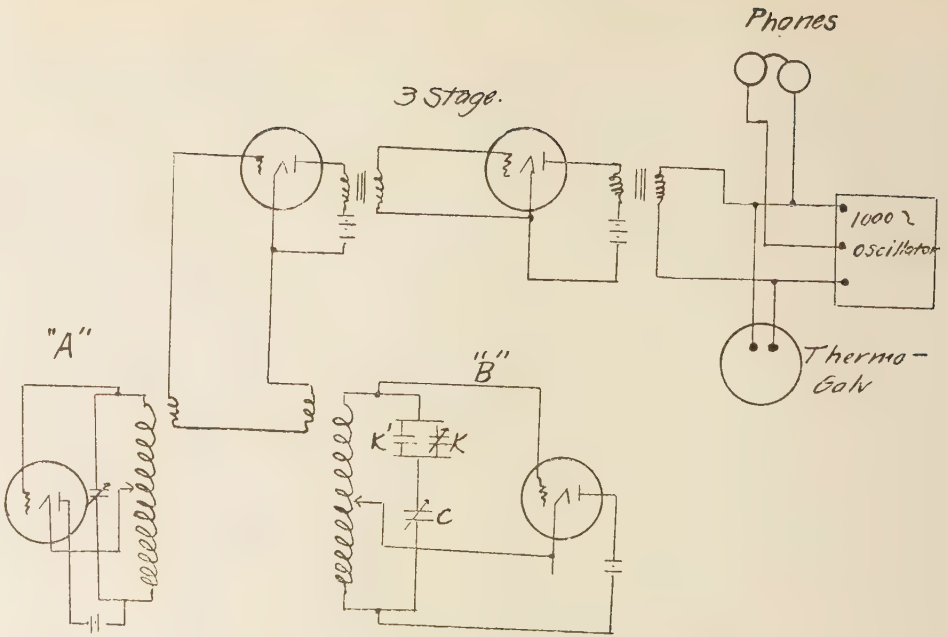

Fig. II. - Schematic Diagram of Electrical Connections

Figure 7th.
% Deviation from Normal
Pressure in Millimeters

obtained by Carman and Hubbard[9] as published by them in the February issue of the *Physical Review* of this year.

It is apparent that the method used in the present determination is better than either the method of Zahn[7] or Fritts[8] because

CAPACITY CHANGES DUE TO PRESSURE VARIATIONS.

Condenser Setting	$t°$	*Test Condenser*	*Pressure in mm. of Mercury*	ΔK *m.m.f.*	ΔC *m.m.f.*	$\%C$	$\%C$. *from atmospheric Pressure*
			TABLE I-A				
1471.0	26.8	14.70	1.5	0.0	0.0000	0.00000	0.0628
1468.0	26.8	14.70	47.0	1.9	0.0709	0.00349	0.0594
1464.0	26.9	14.70	106.0	4.3	0.1602	0.00790	0.0549
1460.0	26.9	14.70	164.0	6.8	0.2534	0.01247	0.0507
1455.0	26.9	14.70	235.5	9.8	0.3650	0.01798	0.0451
1449.0	26.9	14.70	325.0	13.5	0.5030	0.02480	0.0382
1445.0	26.9	14.70	375.5	16.0	0.5960	0.02940	0.0336
1440.5	26.9	14.70	441.5	18.7	0.6970	0.03430	0.0286
1436.0	27.0	14.70	517.0	21.45	0.8000	0.03940	0.0236
1431.0	27.0	14.70	578.5	24.5	0.9130	0.04490	0.0178
1427.0	27.0	14.70	629.0	26.9	1.0010	0.04900	0.0135
1424.0	27.0	14.70	672.5	28.75	1.0700	0.05260	0.0101
1415.0	27.0	14.70	754.0	34.24	1.2760	0.06280	0.0000
			TABLE I-B				
1455.0	28.0	14.70	2.0	0.0	0.0000	0.00000	0.0650
1453.0	28.0	14.70	21.5	1.3	0.0474	0.00233	0.0628
1450.0	28.0	14.70	64.0	3.1	0.1155	0.00568	0.0594
1448.0	28.1	14.70	104.5	4.4	0.1640	0.00806	0.0570
1444.5	28.1	14.70	142.0	6.4	0.2380	0.01170	0.0534
1442.0	28.1	14.70	183.0	7.8	0.2910	0.01430	0.0508
1438.0	28.1	14.70	223.5	10.4	0.3880	0.01910	0.0457
1434.0	28.1	14.70	277.0	13.1	0.4890	0.02410	0.0410
1431.8	28.1	14.70	318.0	14.2	0.5290	0.02600	0.0390
1429.0	28.1	14.70	354.0	15.9	0.5930	0.02920	0.0358
1426.0	28.1	14.70	393.0	17.75	0.6620	0.03260	0.0325
1422.5	28.1	14.70	439.0	19.9	0.7410	0.03650	0.0286
1419.0	28.2	14.70	477.0	22.0	0.8210	0.04040	0.0246
1416.0	28.2	14.70	520.5	23.85	0.8880	0.04370	0.0212
1412.0	28.2	14.70	565.0	26.3	0.9800	0.04810	0.0167
1410.0	28.2	14.70	599.0	27.5	1.0250	0.05050	0.0151
1406.0	28.2	14.70	642.0	29.94	1.1150	0.05480	0.0101
1403.0	28.2	14.70	686.5	31.7	1.1800	0.05810	0.0069
1401.0	28.2	14.70	722.5	33.0	1.2290	0.06050	0.0045
1397.0	28.2	14.70	754.5	35.4	1.3200	0.06500	0.0000

[7] C. T. Zahn, Phys. Rev., 24, 401 (1924).
[8] E. C. Fritts, Phys. Rev., 23, 345 (1924).
[9] Carman and Hubbard, Phys. Rev., 29, 299 (1927).

the capacity under test was relatively large while the lead capacities were very small in proportion to the condenser used. This, of course, means a smaller per cent error in the calibration of the condenser system, for it is in the calibration that the possibility of error is greatest.

From the observed data it was found that the change in capacity due to a change of relative humidity from 7% to 97%, the minimum and maximum values reached, was only 1.296 m.m.f. This gave then a maximum change of 0.0638 of one per cent. Table II gives the results as obtained.

CAPACITY CHANGES DUE TO HUMIDITY VARIATIONS

% Humidity	*Condenser Setting*	*t°*	*Test Condenser*	*Pressure in mm. of Mercury*	*ΔK m.m.f.*	*ΔC m.m.f.*	*%C*	*% C from 50 % Humidity*
				Table II-A				
7.0	1363.0	26.8	14.70	753	00.00	0.000	0.00000	0.0295
17.0	1352.0	26.8	14.70	753	06.73	0.251	0.01235	0.0152
44.5	1345.0	26.8	14.70	753	11.03	0.411	0.02020	0.0093
56.8	1332.0	26.9	14.70	753	18.93	0.705	0.03470	0.0051
95.0	1310.0	27.0	14.70	753	32.38	1.208	0.05950	0.0299
				Table II-B				
15.0	1361.0	26.5	14.70	761	00.00	0.000	0.00000	0.0300
28.0	1352.0	27.0	14.70	761	05.49	0.204	0.01000	0.0199
43.0	1337.0	27.0	14.70	761	14.65	0.546	0.02680	0.0030
57.0	1331.0	27.1	14.70	761	18.30	0.681	0.03350	0.0036
85.0	1323.0	27.2	14.70	761	23.20	0.865	0.04260	0.0125

Taking a value of 50 per cent humidity as an average, the results proved that the greatest per cent change in going from this value to saturation was only 0.0312, while a change from 50 per cent to dryness resulted in a per cent change of 0.0298.

VI. THE DISCUSSION OF RESULTS

From the results obtained in this investigation, the effect of a pressure or a humidity change can be shown to be negligible, that is for all practical purposes. This is made clear in the following example:

Using a tuned circuit of a natural wave length of 500 meters containing an inductance of 35.216 microhenries and a capacity of 2,000 m.m.f., the following relation holds true:

$$\lambda = 11.181 \sqrt{C} = 500 \text{ meters}$$

The wave length at normal pressure would then be 500.00 meters.

The wave length at a pressure of 675 mm., which is lower than any atmospheric reading, would be 500.18 meters.

With the same circuit the maximum relative humidity change from 50% is only 0.0298%, giving a wave length of 500.97 meters.

These changes, occurring in an ordinary receiving set or in an oscillating vacuum tube set, would affect the tuning in a manner entirely negligible.

VII. VITA

George Daniel Rock was born at Bridgeport, Connecticut, September 21, 1899. He received his elementary school training in the public schools of the same place. His college preparatory work was done at the Bridgeport High School, from which institution he was graduated in June, 1917. He received his undergraduate training at the Catholic University of America, attaining the degree of Bachelor of Science in Electrical Engineering, June, 1921. Since September, 1921, he has pursued his graduate studies at the same university, receiving the degree of Master of Arts in June, 1922, and the degree of Electrical Engineer in June, 1924.

The writer takes this opportunity to acknowledge his great obligation to Dr. Daniel W. Shea, of the Department of Physics, for his assistance in procuring the necessary apparatus and for his suggestions and encouragements in the carrying out of the work of the investigation.

The writer wishes also to express his appreciation for the valuable assistance given by Dr. Simon Klosky, of the Department of Chemistry, and by Mr. F. Leo Talbott, of the Department of Physics.